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System for Automating and Multiplexing Soil Moisture Measurement by Time-Domain Reflectometry

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ABSTRACT

It is often necessary to measure soil water content at multiple points in space and time. Our goal was to develop an automated and multiplexed measurement system using time-domain reflectometry (TDR). Two systems are described; the first (A) uses an analog TDR unit, in which voltage signals sent from the TDR to a datalogger convey the shape of the waveform. The second (D) uses a digital TDR that communicates a digital representation of the oscilloscope wave to a personal computer. Both systems use the same multiplexing strategy, in which the TDR transmission line connects through a 12-position rotary switch to various waveguides positioned in the soil and to further rotary switches. The switches are turned by stepping solenoids that are activated by the datalogger in System A and the computer in System D. System D uses software to automatically analyze the incoming waveforms and calculate volumetric water content. Some of the possible uses of each system include observation of infiltration at multiple points within a field and measurement of unfrozen water content as a function of space and time during freezing and thawing. The system has also been used to estimate the reproducibility of water content measurement by TDR, which was found to be in the range of ±0.006 to ±0.008. The systems described should be useful for field research on many subjects, including studies of transport and biological processes in soil, and validation of root water-uptake models.

SOIL WATER CONTENT is a critical variable in many processes and its measurement is thus of importance in many types of studies. It is rarely a static property; indeed, it is often the change in water content with respect to time that is of paramount interest, which requires repeated measurements at the same site. Furthermore, since soil water content often exhibits considerable spatial variability, confident data interpretation may require measurement at a number of sites each time. Such measurement problems can be facilitated by automation and by multiplexing. This paper details a system capable of automated, unattended measurement of water content at multiple sites by a single time-domain reflectometer, and provides preliminary data as well.

Many methods of automating the measurement of soil water status have been reported. However, most involve measurement of water potential rather than water content. These include banks of tensiometers (Rice, 1969; Long and Huck, 1980; Lowery et al., 1986), soil psychrometers (Richards and Caldwell, 1987), and resistance blocks (Armstrong et al., 1985) connected to dataloggers. Water content is a more difficult problem in this regard. The traditional methods of measurement, neutron moderation and gamma attenuation, have been automated in laboratory projects (Herkelrath and Gardner, 1977; Dirksen and Raats, 1985; Hopmans and Dane, 1986; Baker and Van Bavel, 1988), but applications in the field are more rare (Moutonnet et al., 1988). Indeed, unattended field operation of either nuclear method is probably illegal due to the radiation hazard involved. Also, multiplexing either method is difficult because it entails movement of the radiation source and detector from one point to another. Lysimetry offers automated measurement of water-content changes. Multiple-unit installations have been used (Merek et al., 1988), but precision lysimeters are expensive and they are fixed in space. Furthermore, lysimetric data yield no information about distribution of water-content changes unless an additional measurement method is employed.

A relatively new method of soil-moisture measurement, time-domain reflectometry (TDR), has properties that make it amenable to automated control and multiplexing. Signal-transmission lines can be readily fabricated, and the signal can be switched, permitting multiple lines to be used with a single instrument.

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Also, there are no associated health hazards. Herkelrath and Hamburg (1986) discussed an automated TDR system in an oral presentation.

Time-domain reflectometers have been in use for many years in the telecommunications industry for locating faults in coaxial cable. Fellner-Feldeg (1969) showed how TDR could also be used to measure the apparent dielectric constant of liquids, and Davis and Chudobiak (1975, p.75–79) and Topp et al. (1980) applied it to the measurement of the apparent dielectric constant of soil, which is strongly dependent on water content. Topp et al. (1980) demonstrated that TDR could measure water content with an accuracy of better than 2%, and that a single calibration equation could be applied to nearly all soils. The accuracy and utility of TDR has been demonstrated in numerous studies since (e.g., Topp and Davis 1985; Patterson and Smith, 1981; Stein and Kane, 1983), which provide descriptions of the basic principles and methodology.

MATERIALS AND METHODS

Instrumentation

The initial system (System A) was developed around an analog TDR (Model 1502, Tektronix Inc., Beaverton, OR)[1], using a datalogger (CR21X, Campbell Scientific Inc., Logan, UT) to control the multiplexing system and record the waveforms. A second system (System D) was developed with the newer digital TDR (Tektronix Model 1502B) interfaced with a microcomputer to control the TDR, operate the multiplexing system, and record and analyze the waveforms. Much of the following description applies to both systems. Those features peculiar to one system or the other will be noted.

Multiplexing

A schematic of the multiplexing system used is shown in Fig. 1. A 50-ohm coaxial cable (Belden no. 8219) carries microwave pulses from the TDR and is connected through an impedance-matching transformer, or balun (Adams-Russel Corp., Waltham, MA), to 186-ohm fully shielded TV-antenna wire (Belden no. 9090). The antenna wire is connected to the input side of a 12-position, dual-pole, rotary switch (Centralab no. 1412, Fort Dodge, IA) which was found by Herkelrath and Hamburg (1986) to be a suitable, inexpensive switch for TDR transmission lines. The switches are nearly transparent to the TDR, so that waveforms from a transmission line with a switch in it are essentially indistinguishable from those on a continuous line of similar length.

Antenna wire carries the microwave pulse from each of the 11 pairs of output poles to waveguide pairs embedded at different locations in the soil. The waveguides are stainless steel rods, 3 mm in diameter and 300 mm long. If more than 11 measurement sites are desired, the switches can be piggybacked, i.e., one of the pairs of output poles can be connected to the input poles of another switch. In the initial field installation, two of the output terminal pairs were connected to the input terminals of other switches, allowing as many as 31 waveguides from the three switches to be multiplexed through the same TDR. Each switch was coupled to a stepping solenoid powered with 50-V DC current actuated through a relay by 5-V control signals from a datalogger or computer.

[1] Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the author or USDA.

Automation

System A (Fig. 2a) contains an x-y output module, which can output an analog facsimile of the oscilloscope waveform in the form of voltages corresponding to the x and y coordinates of discrete points along the trace. These are recorded by the datalogger for subsequent downloading to a microcomputer, where they are analyzed. The datalogger can cycle with sufficient speed to obtain as many as 1000 data points for each waveform sent, but this fills the memory rapidly and unnecessarily. We found that recording on every fifth datalogger cycle provided a sufficient number of points ($\approx$200) to accurately reproduce each trace. The 1502 TDR generates analog output only when a toggle switch on the panel is depressed, which is an obstacle to complete automation. It may be possible to bypass the switch to place output control at the datalogger, but Tektronix provides no guidance on the subject and advised that removal of the front panel for further investigation would void the warranty.

The central component of System D (Fig. 2b) is a digital TDR, which can communicate with, and be controlled by, a personal computer. The TDR digitizes the waveform, using 250 discrete points to represent each oscilloscope trace. The instrument used has a parallel-output port that connects via a cable to a parallel I/O board (Metrabyte Corp., Taunton, MA), which resides in a slot in an IBM PC-AT. Subsequent to the development of this system, a device has become available from Tektronix that converts the TDR parallel port to a serial port, obviating the need for an extra board in the computer. This has the additional advantage of permitting a longer cable between the TDR and the com-

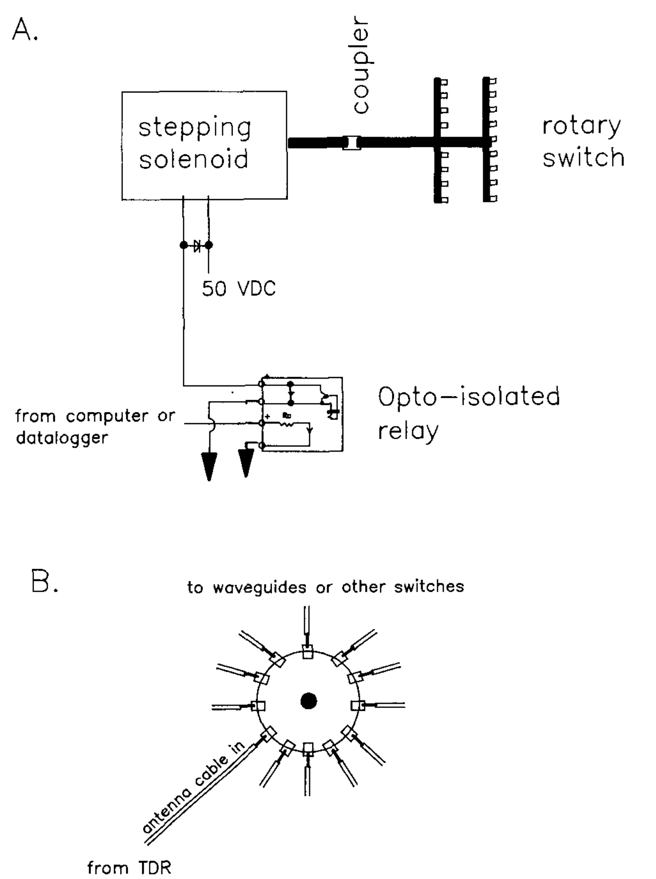

Fig. 1. Schematic of the multiplexing system for time-domain reflectometry (TDR). A. End view of the 12-position switch. B. Side view of the solenoid/switch assembly.

puter without the timing problems that occur when one attempts to use longer runs of parallel cable.

Electromechanical control of the rotary multiplexing switch is accomplished by coupling the shaft of the switch to the shaft of a 12-position stepping solenoid (Lucas-Ledex Inc., Vandalia, OH), as in Fig. 1a. The solenoid requires a higher voltage level and more current than a computer or a datalogger can supply directly. A 5-V TTL level relay, capable of carrying 2 A from a 50-V DC power supply to the solenoid, is required. In System A, reed relays were used, which were activated by 5-V excitation pulses of 400 ms duration from the datalogger. In System D, solid-state relays were used, which were driven by 5-V signals from the parallel I/O card in the microcomputer.

Software for communicating between the PC and the TDR was developed, starting from PASCAL algorithms supplied by Tektronix. These were modified and adapted to our particular purpose, with additional procedures written to drive the multiplexing switches. A separate procedure was written to analyze the waveforms generated by each measurement, so that the data could be reduced at the time of collection. This greatly decreased the data-storage space required, which can be a factor if many sites are being measured or if a rapid scanning interval is being used.

The analysis procedure identifies the reflection points on the digitized waveform in the following manner. The waveform is first smoothed and differentiated, using least-squares procedures of Savitsky and Golay (1964). Then the global minimum of the smoothed waveform is found, after which a local maximum is found over the region from the start of the trace up to the global minimum. The next step is to find the most negative first derivative over a region of 25 data points (one major division on the oscilloscope screen), starting from the local maximum of the smoothed curve. The slope that is thus identified is combined with the corresponding point on the smoothed trace to give an equation of a line tangent to the curve at that point. The intersection of that tangent line with a horizontal one passing through the local maximum of the smoothed trace identifies the initial reflection. The final reflection is similarly identified, beginning from the global minimum and maximizing the first derivative over the ensuing region of 25 points. The apparent distance, L_a, between the initial and final reflections follows directly, using the distance/division setting of the TDR, and it is used with the known waveguide length, L, to calculate the apparent dielectric constant, $K_a = (L_a/L)^2$. Volumetric water content is then calculated using the general Eq. [1] of Topp et al. (1980)

$$\Theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}K_a - 5.5 \times 10^{-4}K_a^2 + 4.3 \times 10^{-6}K_a^3 \qquad [1]$$

Computer analysis of the TDR traces not only facilitates automation, but also systematizes the measurement, eliminating bias and variability among individuals that can result when traces are analyzed by hand. It is, however, advisable to include error-trapping routines that flag suspicious or unusual waveforms for subsequent inspection. These might include waveforms producing unrealistic water contents, waveforms in which the initial reflection is displaced from its normal location, or waveforms in which the slope of the final reflection is unusually flat, indicating a poorly defined reflection. We have since included a standard on one of the multiplexers, which consists of a PVC canister filled with soil and sealed to prevent water-content changes. A waveguide pair embedded in the soil in the standard is connected to the rotary switch as the other waveguides are, so that each set of measurements includes a standard water content. This is a precaution against instrument drift although, to this point, no drift has been observed. Output from both TDR units was checked against neutron and gravimetric data to confirm the applicability of Eq. [1] for the soil and instruments in question.

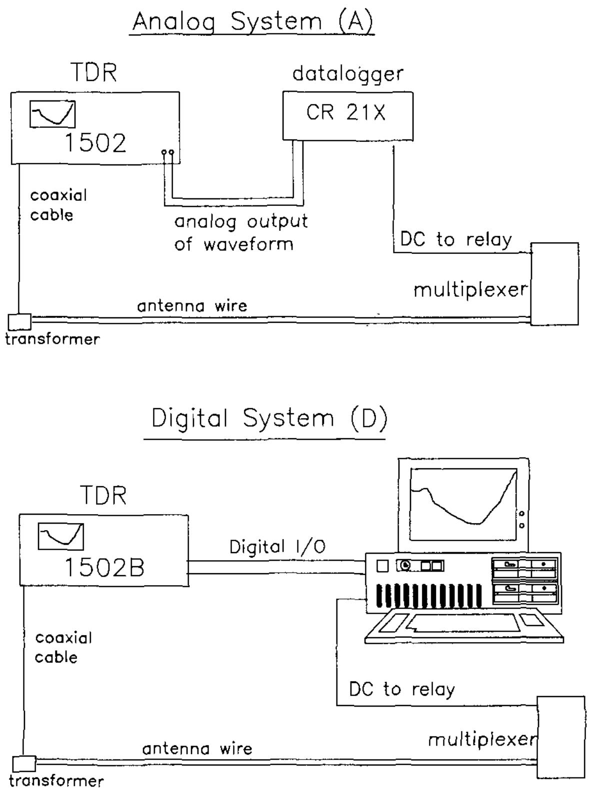

Fig. 2. A. The analog time-domain reflectometry (TDR) automation system, which is controlled by an operator. B. The digital TDR automation system, which can be controlled by a personal computer.

Field Installation

System A. The initial analog TDR system was installed in an alfalfa (*Medicago sativa* L.) field at the University of Minnesota Agricultural Experiment Station at Rosemount, MN (44° 45′ N, 93°W). In June of 1988 a 2-m by 1-m by 1-m-deep pit was dug by backhoe. On each of the two long walls of the pit, 12 pairs of waveguides were installed horizontally as shown in Fig. 3. Two additional pairs were later

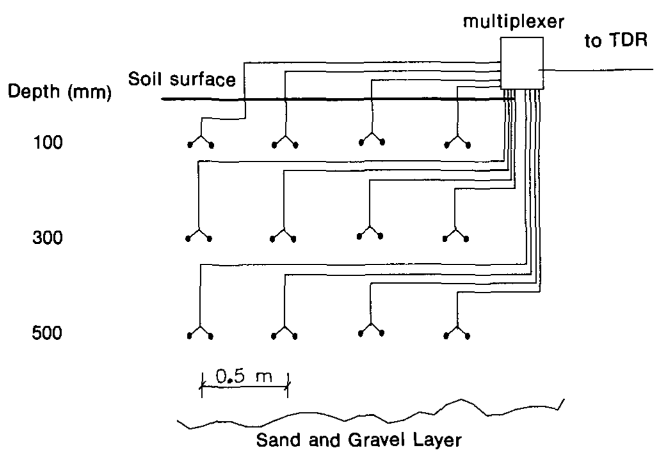

Fig. 3. Field installation of the time-domain reflectometry (TDR) system. This is a vertical view of one sidewall of the pit. The other side was similarly instrumented.

for each pair, a cavity was excavated to a depth of 0.1 m into the face of the pit wall. Then two 3-mm holes spaced 50 mm apart were drilled horizontal to the pit face into the back of the cavity, using a jig and a level to keep them evenly spaced and parallel to the soil surface. The stainless steel waveguides, which were 300 mm in length, were inserted into these holes and firmly pushed in. Spatial sensitivity of TDR (Baker & Lascano, 1989) indicates that waveguides of this length and orientation measure the water content of a volume of soil of approximately 70 mm wide, 30 mm high, and 300 mm in length.

Equal lengths of antenna wire were connected to each waveguide pair, so that all oscilloscope traces would be visible with the same distance setting on the TDR. The pit was then backfilled, with care taken to replace soil at the depth from which it had been removed, to the extent possible, and the surface of the pit was reseeded with alfalfa. The antenna wires were fed into an all-weather electrical enclosure (NEMA type-12) in which they were connected to the previously described 12-position, solenoid-driven switches. The datalogger, TDR, and power supply were housed in a trailer located approximately 30 m from the pit and the NEMA enclosure. A neutron-access tube was installed on each side of the pit, approximately 2 m from the pit face.

Operation of this system was controlled with a program on the datalogger that pulsed the appropriate switch, then waited for the operator to send an analog facsimile of a trace by toggling a switch on the TDR. Recording of a complete set of 26 traces required approximately 15 min. These data then had to be transferred to a computer in the laboratory for analysis.

System D. The digital system superseded the analog system described above. It uses the same waveguide and switch installation, but with the digital TDR in place of the analog version and an IBM microcomputer in place of the datalogger. The second system is completely automated so that the presence of an operator is not required. A batch file on the computer activates the appropriate switch via a relay, then signals the TDR to acquire and transmit a waveform. The waveform is analyzed to solve for volumetric water content, then the appropriate switch is moved and the process is repeated. A complete measurement cycle through all 26 waveguides requires approximately 3 min. The system can be programmed to cycle through all waveguides on a fixed time schedule, or in response to logic dependent on factors such as meteorological inputs.

RESULTS AND DISCUSSION

The data presented are intended primarily as examples of what can be done with automated and multiplexed TDR arrays. System A was used to follow the freezing and thawing of the profile through the winter of 1988-1989, using the installation previously described. Readings were taken on approximately a weekly basis, and used in concert with neutron readings taken at the same time to delineate the liquid and frozen volumetric-water-content profiles at each point in time, similar to the approach taken by Hayhoe et al. (1983). This usage takes advantage of the fact that the dielectric constant of ice is essentially the same as that of dry soil and much smaller than that of water, so TDR measures only liquid water content in partly frozen soil, while neutron moderation is sensitive to all forms of water (Patterson and Smith, 1981). Three of the results obtained are shown in Fig. 4. The total water-content profiles for the first two dates are nearly indistinguishable, suggesting little net movement of water, but the partitioning between water and ice, indicated by the TDR readings, changed dramatically as the soil partially thawed. By 12 April, thermocouple readings indicated that the last of the ice was melting, and the convergence of the TDR and neutron profiles confirms this. The system performed throughout the winter, at temperatures as low as −25 °C, with no significant problems. The data collected will be used with associated meteorological data in validation of a model of heat and mass transfer in freezing/thawing soils.

System D became operational in the early spring of 1989, and has been in use since. It routinely measures at all 26 sites on an hourly basis, but the scan interval can be changed. Figure 5 shows hourly values for 8

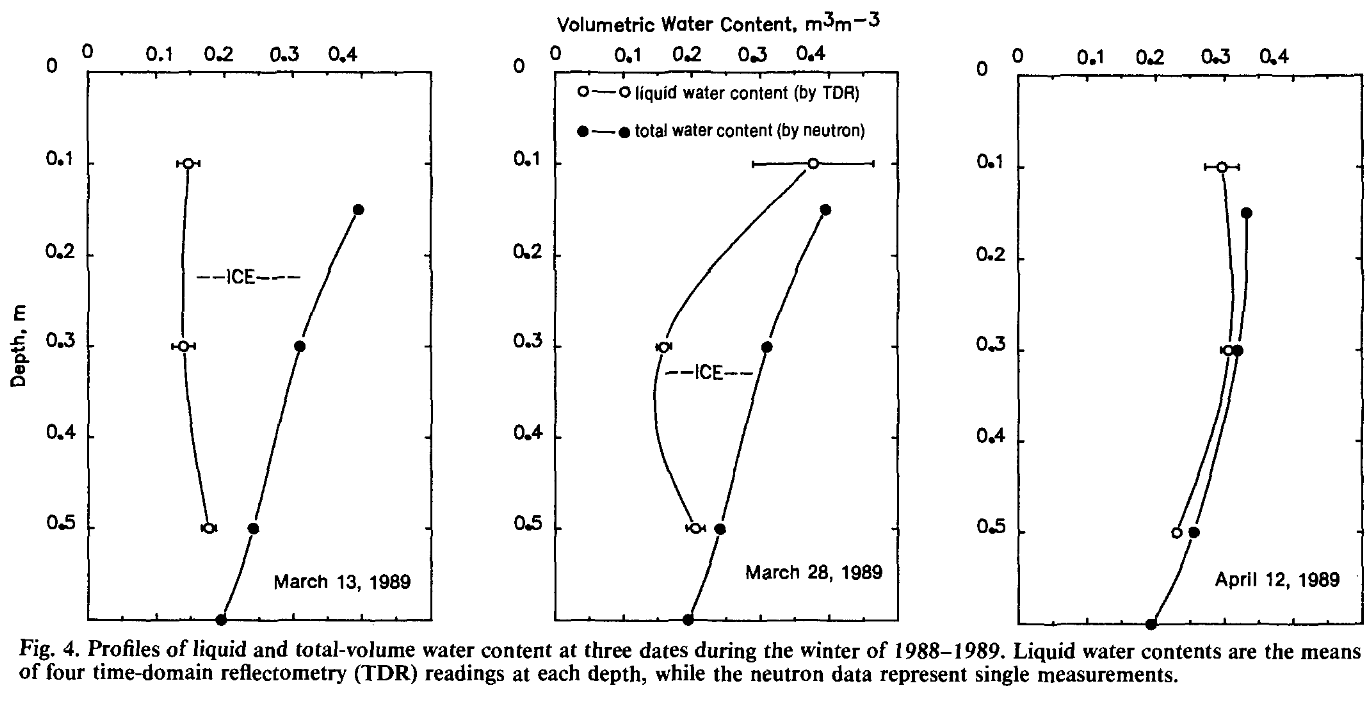

Fig. 4. Profiles of liquid and total-volume water content at three dates during the winter of 1988–1989. Liquid water contents are the means of four time-domain reflectometry (TDR) readings at each depth, while the neutron data represent single measurements.

May 1989, a day on which 22.4 mm of rainfall fell during the afternoon. Table 1 gives a simple water balance for each of the four profiles north of the original installation pit, done by assuming that the waveguides at 100-, 300-, and 500-mm depth each represents a layer of soil extending 100 mm above and below, for a total profile depth of 600 mm. There are substantial differences among the four profiles, indicating nonuniformities in the infiltration process, even though the rainfall was not sufficiently intense to produce surface ponding. Though there are large differences between the profiles, however, the mean change in water content for the four profiles is remarkably close to the total rainfall recorded. This is

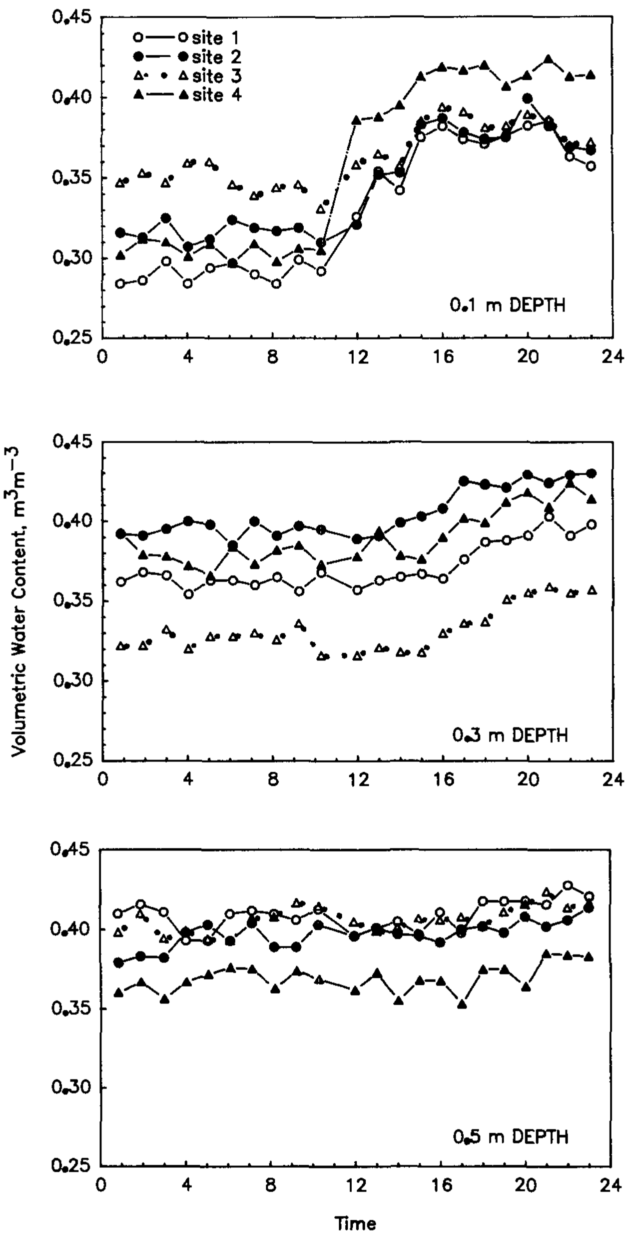

Fig. 5. Changes in soil water content associated with a 22-mm rainfall event on 8 May 1989. Data shown are for the 12 waveguides to the north of the pit (three depths for each of four profiles). These were recorded and analyzed on an hourly basis by the automatic digital unit.

similar to the results reported by Van Wesenbeeck and Kachanoski (1988). Also, though the net changes are quite variable among the sites and depths, the final water contents of all sites are quite similar, suggesting lateral redistribution.

In time-dependent problems, the precision or reproducibility of the measurement method is generally of more importance than the absolute accuracy. To this point, however, more has been written regarding the accuracy of TDR than the precision. Topp and Davis (1985) reported a reproducibility of ± 0.01 in water content. One of the benefits of an automated network of in situ sensors is that it allows examination of reproducibility, as well as simultaneous study of spatial and temporal variability in volume water content. Detailed analyses of these questions strays from our purpose, but some preliminary observations are appropriate.

Table 2 lists data for 3 to 4 May 1989, which was 5 d after the most recent rainfall, and was cool, cloudy, and early enough in the spring so that water uptake by the alfalfa was negligible. It shows the hourly readings for four waveguide pairs at the 0.3-m depth.

Table 1. Water balance for each of the four profiles of Fig. 5 for the 8 May 1989 rainfall event.

		Net Increase in Water Content, mm					
		Profile					
Layer	Depth, mm	Site 1	Site 2	Site 3	Site 4	Mean	SD
1	0–200	14.6	10.2	5.0	22.4	13.0	6.38
2	200–400	7.2	7.6	7.0	4.2	6.5	1.35
3	400–600	2.2	7.0	3.8	4.6	4.4	1.73
Total	0–600	24.0	24.8	15.8	31.2	23.9†	5.47

† Rainfall = 22.4 mm.

Table 2. Measured hourly water contents for each of the four sites at the 0.3-m depth on the north side of the pit for 3–4 May 1989. The means and the standard deviations for the four points are given, as are the means and standard deviations for the entire day for each individual measurement point.

	Volumetric Water Content					
	Measurement Site					
Hour	1	2	3	4	Mean	SD
1	0.414	0.407	0.421	0.357	0.400	0.025
2	0.407	0.401	0.419	0.372	0.400	0.017
3	0.430	0.411	0.409	0.364	0.403	0.024
4	0.407	0.397	0.409	0.370	0.396	0.016
5	0.423	0.397	0.402	0.379	0.400	0.016
6	0.403	0.410	0.415	0.371	0.400	0.017
7	0.417	0.411	0.420	0.371	0.405	0.020
8	0.415	0.401	0.406	0.377	0.400	0.014
9	0.410	0.393	0.411	0.368	0.395	0.017
10	0.411	0.402	0.405	0.373	0.398	0.015
11	0.405	0.404	0.406	0.365	0.395	0.017
12	0.413	0.406	0.402	0.375	0.399	0.014
13	0.421	0.398	0.398	0.370	0.397	0.018
14	0.408	0.398	0.399	0.374	0.395	0.013
15	0.412	0.387	0.395	0.381	0.394	0.012
16	0.417	0.397	0.416	0.369	0.400	0.019
17	0.422	0.385	0.400	0.377	0.396	0.017
18	0.413	0.392	0.406	0.368	0.395	0.017
19	0.434	0.403	0.404	0.372	0.403	0.022
20	0.428	0.408	0.406	0.392	0.408	0.013
21	0.428	0.384	0.415	0.365	0.398	0.025
22	0.423	0.394	0.421	0.373	0.403	0.021
23	0.415	0.404	0.413	0.379	0.403	0.014
Mean	0.416	0.400	0.409	0.372	0.399	0.018
SD	0.008	0.008	0.008	0.007	0.004	

Means and standard errors are shown for each hour, and they are given as well for each waveguide pair at the bottom of the table, pooling the 23 hourly measurements. The data from the individual waveguide pairs show standard deviations ranging from ±0.004 to ±0.008, which are much smaller than the typical standard errors of the mean at any point in time. This was true for the waveguide pairs at the other depths as well. These data indicate the hazard of routinely pooling the information from the individual waveguide pairs at each depth. The precision of the method is such that this procedure is tantamount to throwing away information; it "linearizes" a variable whose changes are the result of nonlinear operators. Such pooling only makes sense if the precision, or measurement error, exceeds the spatial variation, expressed as the standard deviation among the measurement sites at a given point in time.

Obvious additional uses of an automated TDR system include measurement of changes in water content associated with root uptake, and simultaneous automated measurement of water content by TDR and water potential by tensiometers, soil psychrometers, or resistance blocks. These would facilitate model validation and allow routine use of such procedures as the instantaneous-profile method (Van Bavel et al., 1968) to track changes in soil transport properties.

SUMMARY

Time-domain reflectometry allows multiplexed, automated, in situ measurement of soil volumetric water content. The system described has been rugged and reliable, yielding measurements throughout winter and through rainfall events with only minor problems. The system has allowed estimation of the precision of TDR for moisture measurement, which was found to be approximately ±0.006. Some preliminary data have been included that demonstrate some of the possible uses of an automated array of TDR waveguides, including measurement of freezing and thawing of soil water and measurement of infiltration during rainfall.

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